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Direct measurement of the group index of photonic crystal waveguides via Fourier transform spectral interferometry

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The authors report a direct, single-shot measurement of the group index profile of photonic crystal waveguides, combining spectral interferometry with Fourier transform analysis. This technique's versatility allows them to resolve subtle changes in dispersion and to quantify the "slow light" effect at the photonic crystal waveguide mode cutoff. For a waveguide 99 μm long, they measure a group index up to 85, whereas for lengths of 397 and 695 μm, they measure maximum values of 30 and 25, respectively. These results show the relationship between transmission characteristics and the maximum group delay observed in photonic crystals. © *2007 American Institute of Physics*.
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Slow light phenomena hold promise of ground-breaking applications in all-optical switching and storage, and are currently the subject of extensive research.[1] A reduced group velocity (v_g) may be exploited to achieve tunable delays or to enhance various optical nonlinearities by virtue of an increased light-matter interaction. Line-defect waveguides with one or several lines of holes removed are of special interest, as they may exhibit large group indices n_g (or equivalently, a small $v_g = c/n_g$) with ultraslow light ($n_g \sim 1000$) having already been observed.[2]

A direct and reliable measurement of the group index is clearly very useful for the characterization of photonic crystal waveguides (PhCWs). Current experimental approaches to the problem include resolving the Fabry-Pérot (F-P) fringes in the transmission spectrum,[3] a variety of time-of-flight (ToF) measurements,[4] and interferometric techniques.[5,6] Here, Fourier transform (FT) spectral interferometry is used to fully map the group index profile of a set of state-of-the-art PhCWs.[7] These were processed all at once as part of the same sample and differ only in length. Comparison of the transmission and dispersion profiles therefore illustrates the influence of fabrication imperfections, more pronounced over longer propagation distances, in the optical properties of such structures.

The high-quality PhC sample was fabricated on a silicon-on-insulator wafer. It contains a set of single line-defect ($W1$) waveguides of lengths 99, 397, and 695 μm. In all of them, a lattice constant of $a = 430$ nm and a hole radius $r = 120$ nm were used, achieving propagation losses below 10 dB/cm (mostly caused by sidewall roughness[7]). Two sections of ridge waveguide conduct the light into each of the PhCWs. The sample also includes a blank (no PhC) ridge waveguide, with a known effective index of 2.7, used in the calibration of the measurements.

The sample is placed in one of the arms of a Mach-Zehnder interferometer (MZI), as shown in Fig. 1. TE-polarized light from an amplified spontaneous emission broadband source is coupled into the waveguide using microscope objectives, and then combined at the output with that of the reference arm. This yields interference fringes, at a period inversely proportional to the optical path difference between the two beams, which are resolved by an optical spectrum analyzer (OSA). Figure 2 shows the interferograms measured for (a) the blank ridge waveguide and [(b)–(d)] the 99, 397, and 695 μm long PhCWs, respectively. The phase shift between two adjacent maxima (minima) of the oscillations is 2π, as they correspond to constructive (destructive) interference. The fringe spacing is constant in the nondispersive ridge waveguide (a). In [(b)–(d)], however, the fringes converge as the wavelength approaches the $W1$ mode edge indicating a significant slowing of the light. Beyond the $W1$ cutoff wavelength fringes are no longer visible and no information on dispersion can be obtained.

The group index can be extracted from the fringe spacing as a function of wavelength, albeit only for a limited number of points. This method is also hindered by the Fabry-Pérot modulation and carries a larger amount of uncertainty when interference extrema converge tightly in the vicinity of the cutoff. FT techniques,[8] on the other hand, provide a continuous mapping of the dispersion profile. Taking the mathematical expression of an interferogram,

$$I(\omega) = S(\omega) + R(\omega) + \sqrt{S(\omega)R(\omega)}\{\exp[i\Phi(\omega) - i\omega\tau] + \text{c.c.}\}, \quad (1)$$

where $S(\omega)$ and $R(\omega)$ are the spectral densities of the sample and reference beams, respectively. By means of a translation stage in the reference arm, the delay τ is initially chosen to obtain a tight fringe spacing (although still within our reso-

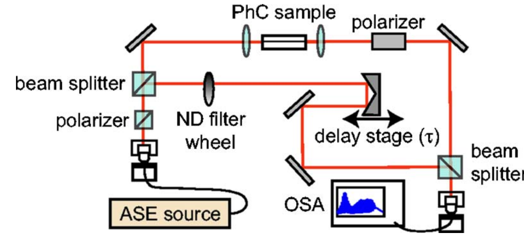

FIG. 1. (Color online) Sketch of the Mach-Zehnder interferometric setup. The delay line (τ) is set such that the reference arm is the shortest, and kept fixed throughout all the measurements presented here (note that no mechanical delay scan is required).

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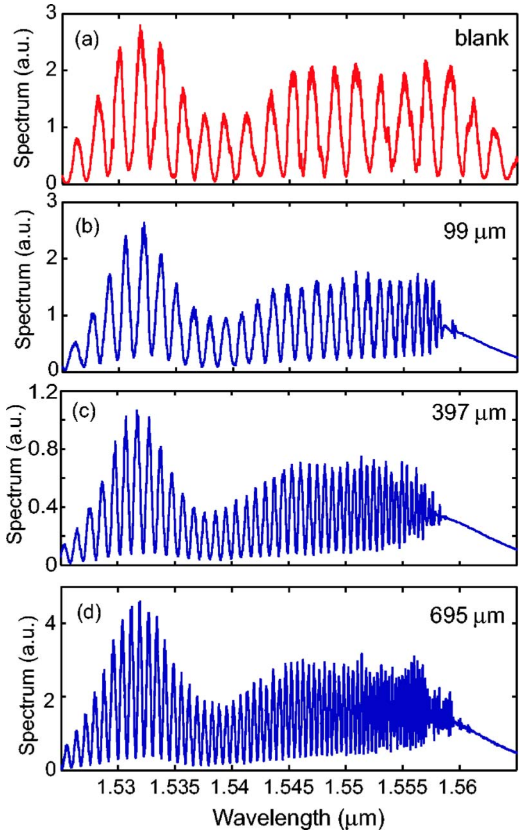

FIG. 2. (Color online) Spectra of the MZI output measured for (a) the blank ridge waveguide, and [(b)–(d)] the PhCWs in order of increasing length.

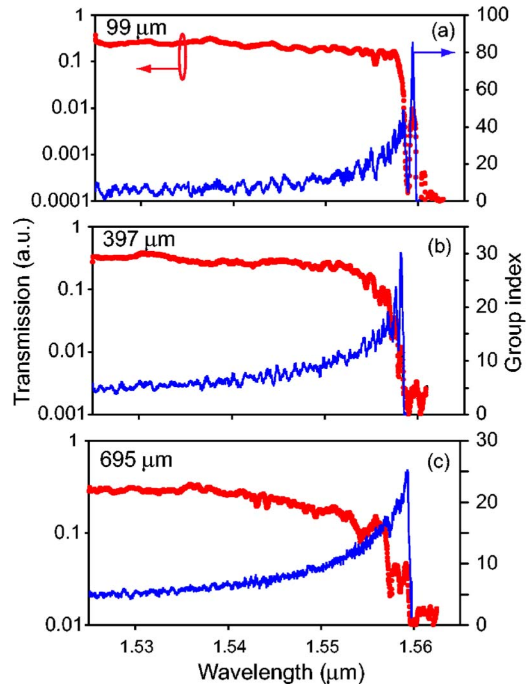

FIG. 3. (Color online) Group index profile (continuous line) and transmission spectra (circles) of the PhC waveguides, namely, (a) 99 μm, (b) 397 μm, and (c) 695 μm.

lution even at the cutoff) and it was kept fixed throughout the measurements reported here (no delay scan is required in this technique). Our choice of τ deliberately made the reference arm the shortest, so that the slowing of the light in the PhCW *increases* the difference in group delay between the two arms and thus leads to a *decrease* of the fringe spacing (see Fig. 2). The information on the dispersive properties of the system is entirely contained in the phase difference term $\Phi = \phi_S - \phi_R$ [Eq. (1)]. The latter is extracted by calculating the Fourier transform of the interferogram with respect to frequency, which is composed of three peaks. The noninterfering terms give a peak centered at $t=0$, while the term $\sqrt{S \cdot R}\exp[i(\Phi - \omega\tau)]$ and its c.c. (c.c. denotes complex conjugate) give peaks shifted to $t=\tau$ and $t=-\tau$, respectively. Having chosen a large enough τ, one of the crossed terms can be numerically filtered and transformed back into the frequency domain, giving $\Phi(\omega)-\omega\tau$. By blocking each corresponding arm of the interferometer in turn, we also measured $S(\omega)$ and $R(\omega)$ to calculate the transmission spectra of the PhC waveguides. This allows us to subtract the noninterfering background [first two terms in Eq. (1)] from the interferograms, and thus optimize the filtering.

The difference in group delay between the two arms of the MZI was obtained by differentiating $\Phi(\omega)-\omega\tau$ with respect to ω, for each of the PhCWs ($\Delta\tau_g^{\mathrm{PhC}}$) and also the blank ridge waveguide ($\Delta\tau_g^{\mathrm{cal}}$). The corresponding group indices were then calculated as

$$n_g = (\Delta\tau_g^{\mathrm{PhC}} - \Delta\tau_g^{\mathrm{cal}})c/L + n_{\mathrm{cal}}, \tag{2}$$

where L is the waveguide length and n_{cal}(=2.7) is the effective index in the ridge waveguide. The group delay in the PhC waveguides is accurately singled out through the calibration run, while the contribution of every other optical element in the setup (including the delay line, τ) is subtracted. It should be noted that reflections at the end facets of the sample cause characteristic Fabry-Pérot resonances in the measured transmission spectra. This contribution to the group delay change was removed by performing a running average on the phase extracted from the interferograms, prior to numerical differentiation (0.4 nm averaging window, approximately twice the F-P period). For consistency, an analogous smoothing was carried out on the transmission spectra of Fig. 3, hence the absence of this F-P modulation.

By applying FT analysis to spectral interferometry measurements, the group index in the PhC waveguides is calculated directly from its definition, $n_g = c(\partial\omega/\partial k)^{-1}$. While ToF experiments can be limited by the heavy distortion of optical pulses in the photonic band gap region, our measurements employ a broadband source and allow characterization over a large spectral range in a stable and repeatable fashion. Interferograms are recorded by the OSA in a single shot, and the FT analysis avoids the need for determining the position of the fringe extrema[9] or nonlinear fitting.[6]

The extracted group index profiles and the corresponding transmission spectra are displayed in Fig. 3. In all three plots the measured group index, starting from a common value close to 5, increases sharply as the edge of the $W1$ mode cutoff is approached. Within the general trend of decreasing transmission/increasing group index, some oscillations can be observed in the dispersion and transmission profiles near the band edge. Moreover, against the general trend, local maxima of n_g and transmission peaks appear to coincide. A similar behavior has previously been observed, without explanation, in ToF measurements.[4] This indicates that the phenomenon is not an artifact of our technique, instead, we believe that it is related to coupling issues in the slow light regime.[10] Increased reflectivity at the PhC/ridge waveguide interfaces (which only occurs at large values of n_g) results in the formation of a F-P resonator inside the PhC cavity. As we scan through the peak of one of these F-P resonances [e.g., at 1559 nm in Fig. 3(a)], the phase in the resonator changes rapidly. This rapid phase change is superimposed on the phase change due to the waveguide, making the group index larger at a point of high transmission, which is exactly what we observe.

The transmission spectra exhibit a sharper cutoff behavior as shorter waveguides are considered, which can be attributed to the light experiencing less total loss. Furthermore, our results provide quantitative evidence of this effect in the maximum group delay of the PhCWs under study. The maximum value of n_g, observed at the cutoff wavelength, decreases from approximately 85 in the 99 μm case, to 30 and 25 for lengths of 397 and 695 μm, respectively. The contribution of the above F-P phase effect cannot in itself explain this decrease with length (which, interestingly, is comparatively smaller between the two longest waveguides). Larger group indices reported previously[3] correspond to much shorter waveguides (approximately 30 μm), to some extent agreeing with the trend observed here. Note that for a sevenfold increase in waveguide length, we measure only a twofold increase of the maximum optical path length ($n_g^{\max}L$). Therefore, the measured maximum group delay does not scale linearly with physical length. We believe that the reason for this unusual behavior is the superlinear relationship between optical loss and group velocity near the $W1$ cutoff frequency.[11]

The experimental uncertainty in the measured group indices is mostly caused by random phase fluctuations along the free-space optical path in both arms of the MZI. This effect is greatly minimized by the phase smoothing step (which at most would lead to a slight underestimation of the group index), and becomes negligible when larger group delays are measured [see Figs. 3(b) and 3(c)].

In this letter, the group index of photonic crystal waveguides is determined by combining Fourier transform analysis with white-light spectral interferometry. This single-shot frequency-domain technique provides a continuous dispersion profile of the sample, not limited to the wavelengths of the fringe extrema, and avoids the need for delay scans. We demonstrate that this rapid and versatile tool is capable of quantifying the "slow light" effect in a range of low-loss silicon-on-insulator $W1$ PhC waveguides. We also highlight the phase distortion caused by F-P oscillations that depend on the matching between the PhC and the ridge waveguide, which is especially critical for low group velocities. The results show a threefold decrease of the group index at the $W1$ cutoff, from 85 to 30 and finally 25, with increasing waveguide length (99, 397, and 695 μm, respectively). This effect is accompanied by a smoothing of the transmission cutoff characteristics, indicating the increasing influence of fabrication imperfections (such as sidewall roughness) over longer propagation distances. Our results highlight that maximum group delays measured in short devices do not simply scale up at a one-to-one ratio with increasing device length, e.g., if the goal is to increase the total group delay for a memory or delay device.

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